
Discovery probability of next-generation $0\nu\beta\beta$ decay experiments

M. Agostini, G. Benato and J. A. Detwiler, Phys. Rev. D96 (2017) 053001

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Why searching for $0\nu\beta\beta$ decay?

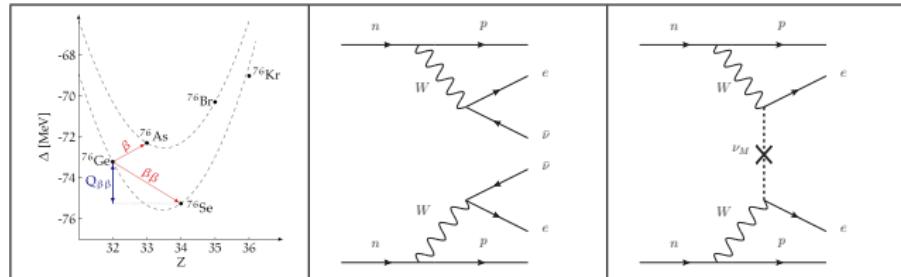
Open questions

- Measured $\Delta m_{\odot}^2, \Delta m_{\text{atm}}^2 > 0$ from oscillation experiments, but in SM and for Dirac neutrinos: $m_1 = m_2 = m_3 = 0$
⇒ What's the mechanism generating ν masses?
- ν is the only known neutral fundamental fermion.
⇒ Is the neutrino a Majorana particle?
- No symmetry justifies total lepton number conservation, but no experimental evidence of its violation is available so far
⇒ Is L a fundamental conserved number?
- Is matter dominated universe (= our existence) due to leptogenesis?

Possible answer: $0\nu\beta\beta$ decay

- Test pure Majorana SM neutrinos
- No new field or symmetry required
- Would prove that ν 's are Majorana particles, independent of the channel
- $(A, Z) \rightarrow (A, Z + 2) + 2e^- \Rightarrow$ matter creating process!

Proposal for new terminology¹



Why current name is not optimal

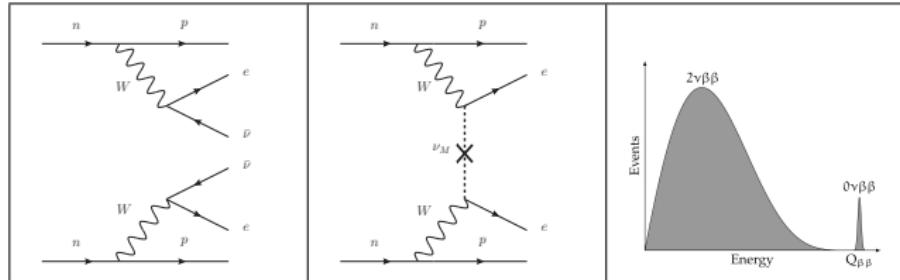
- “ $0\nu\beta\beta$ decay” has historical motivation
- The transition is classified by something it does NOT have
- The definition is not self-contained
- The electron is indicated as “ β -ray”

Proposals for new names (feel free to suggest more!)

- Creation of electrons in a nuclear transformation
- Nuclear electron creation
- Electron creating nuclear process

¹S. Dell'Oro, S. Marcocci and F. Vissani, arXiv:1710.06732

Experimental search for $0\nu\beta\beta$ decay



$\beta\beta$ decay signature

- Continuum for $2\nu\beta\beta$ decay, peak at $Q_{\beta\beta}$ for $0\nu\beta\beta$ decay
- Additional signatures from signal topology, pulse shape discrimination, ...

$0\nu\beta\beta$ decay rate

$$\frac{1}{T_{1/2}^{0\nu}} = G_{0\nu} \cdot |M_{0\nu}|^2 \cdot \frac{|f|^2}{m_e^2}$$

- $T_{1/2}^{0\nu}$ = $0\nu\beta\beta$ decay half life
- $G_{0\nu}$ = phase space (known)
- $M_{0\nu}$ = nuclear matrix element (NME) \Rightarrow factor ~ 2 uncertainty from models
- f = new physics

$O(10^2$ M\$) are going to be invested for an answer

- What return can be expected on this investment?
- What are we capable of, and what should we aim for as a community?

Goals of this work

- What is the discovery probability (DP) of future experiments?
- What sensitivity is of interest?
- On which parameters should optimize and compare experimental designs?

How to allow the comparison of experiments?

Proposal for a common approach

- Energy is the only observable that is necessary and sufficient for discovery
- Fold additional information (topology, pulse shape, ...) into efficiency
- Poisson counting in Region Of Interest (ROI) with (effective) fiducial volume and background level

Formalism

- Sensitive exposure: $\mathcal{E} = m_{iso} \cdot \varepsilon_{ROI} \cdot \varepsilon_{FV} \cdot \varepsilon_{sig} \cdot t$
 - Sensitive background: $\mathcal{B} = \frac{n_{bkg}}{\mathcal{E}}$
 - Number of signal events: $n_{0\nu\beta\beta} = \frac{\ln 2}{T_{1/2}^{0\nu}} \cdot \frac{N_A \cdot \mathcal{E}}{m_a}$
 - Number of background events: $n_{bkg} = \mathcal{B} \cdot \mathcal{E}$
- m_{iso} = isotope mass
 - t = live time
 - N_A = Avogadro number
 - m_a = isotope's molar mass

⇒ \mathcal{B} and \mathcal{E} provide full characterization of $0\nu\beta\beta$ decay experiments
and are naturally suited for comparisons

Experimental sensitivity

Efficiencies

- ε_{ROI} = fraction of $0\nu\beta\beta$ decay events falling in the ROI

$$\varepsilon_{ROI} = \int_{ROI} \frac{1}{\sqrt{2\pi}\sigma} \exp\left(-\frac{(E - Q_{\beta\beta})^2}{2\sigma^2}\right) dE$$

- ε_{FV} = fiducial volume fraction
- $\varepsilon_{sig} = \varepsilon_{MC} \cdot \varepsilon_{cut}$
- ε_{MC} = containment efficiency (fraction of detected $0\nu\beta\beta$ events) from MC
- ε_{cut} = selection efficiency (analysis cuts, excluding FV)

ROI

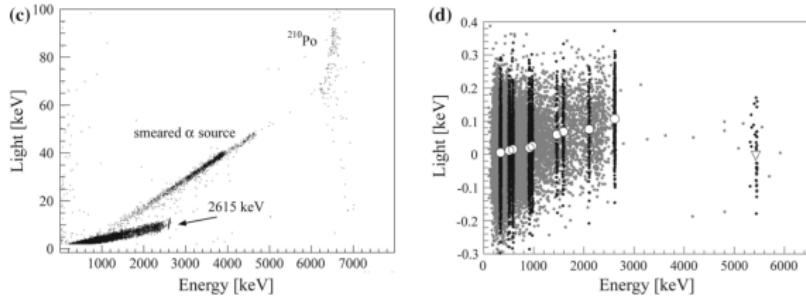
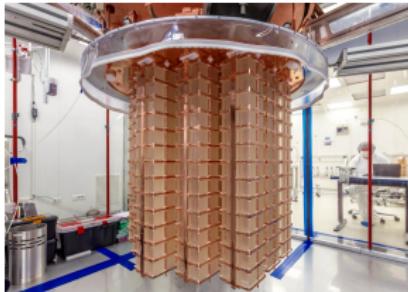
- Chosen based on **(a)** bkg or **(b)** available publications/slides
- If **(a)**, we obtain an optimal ROI of $\pm 2\sigma$ for quasi-background-free experiments, and $\pm 1.4\sigma$ for background-dominated experiments
- Special situation for SuperNEMO (see later)

Experiments

Experiments considered by NSAC*:

- CUORE + CUPID \Rightarrow ^{130}Te (^{82}Se , ^{116}Cd , ^{100}Mo)
- KamLAND-Zen \Rightarrow ^{136}Xe
- LEGEND \Rightarrow ^{76}Ge
- nEXO \Rightarrow ^{136}Xe
- NEXT \Rightarrow ^{136}Xe
- PandaX-III \Rightarrow ^{136}Xe
- SNO+ \Rightarrow ^{130}Te
- SuperNEMO \Rightarrow ^{82}Se

* Report to the NSAC, Nov. 18, 2015

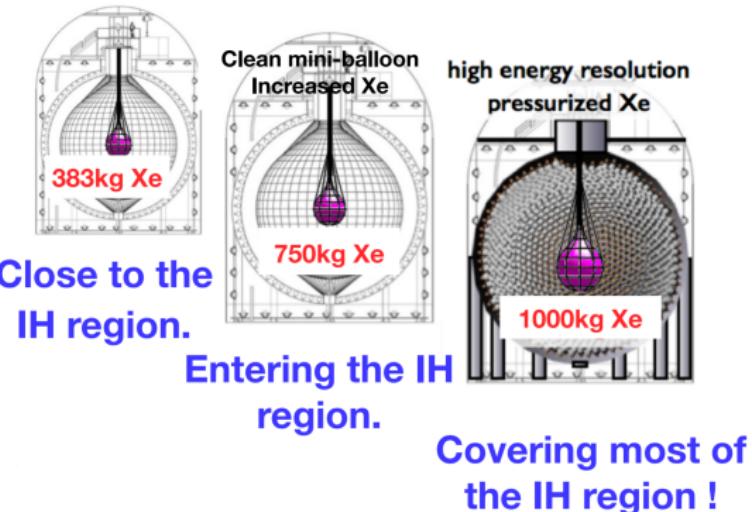


- CUORE: ~ 750 kg of TeO_2 crystals operated as bolometers \Rightarrow Running!
- CUPID: CUORE Upgrade with Particle Identification: α/β discrimination from Cherenkov light (TeO_2) or scintillation light (ZnSe , ...)
- CUPID-0 running with ZnSe !
- CUORE: $\sim 0.2\%$ FWHM, $\text{BI} \sim 10^{-2}$ cts/(keV·kg·yr)
- CUPID: $\sim 0.2\%$ FWHM, $\text{BI} \sim 2 \cdot 10^{-5}$ cts/(keV·kg·yr)
- CUORE background dominated, CUPID quasi-background-free \Rightarrow Different ROIs

CUPID Collaboration, arXiv:1504.03599

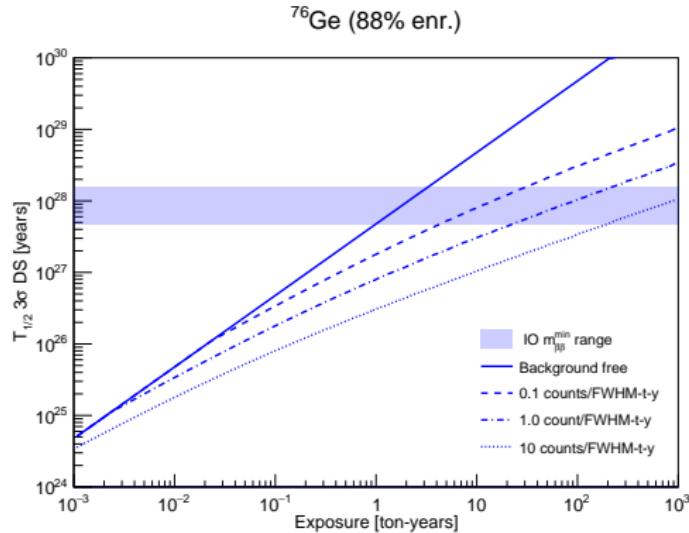
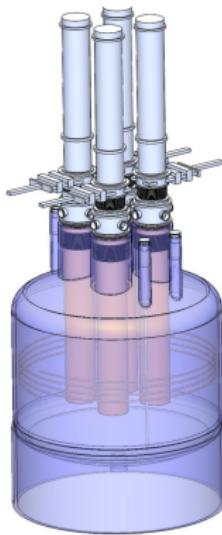
CUPID Collaboration, arXiv:1504.03612

CUORE Collaboration, Eur. Phys. J. C 74 (2014) 3096



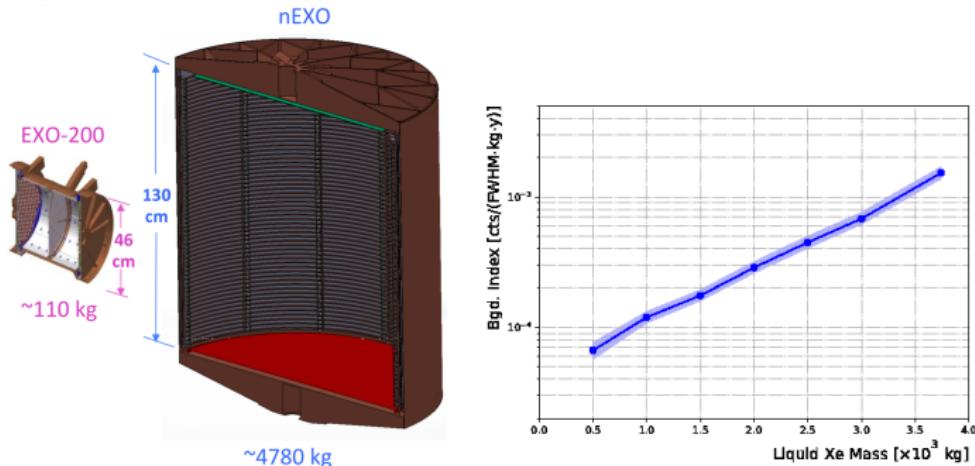
- KamLAND-Zen: upgrade of KamLAND with nylon balloon containing xenon loaded scintillator for $0\nu\beta\beta$ decay search
- KamLAND-Zen 800: 750 kg of ^{136}Xe , background reduction $\times 1.5$, $4.6\% \sigma$
- KamLAND2-Zen: 1 ton of ^{136}Xe , background reduction $\times 15$, $2\% \sigma$
⇒ New liquid scintillator (LAB), new PMTs, light concentrators
- Limited resolution ⇒ Asymmetric ROI

LEGEND



- Newly formed collaboration \simeq GERDA + Majorana + others
- Baseline strategy: germanium detectors enriched to 88% in ^{76}Ge ; liquid argon (LAr) as shielding and active veto
- LEGEND 200: 200 kg in GERDA infrastructure, BI \sim 3 times lower than GERDA-II
- LEGEND 1k: 1 ton in new infrastructure, BI \sim 18 times lower than GERDA-II
- Strategy for background reduction: improved LAr veto, clean materials and components from Majorana

S. Schönert, talk at NeuTel 2017, Venice, 2017

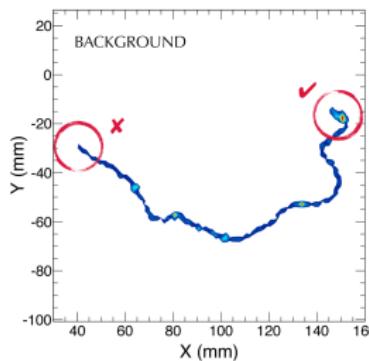
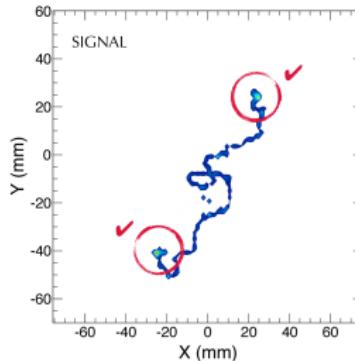


- TPC with 5 ton of liquid xenon 90% enriched in ^{136}Xe
- Large mass of liquid \Rightarrow Self shielding!
- Final analysis done as a function of energy and radius \Rightarrow We reproduce exclusion sensitivity using 3 ton fiducial mass and $4 \cdot 10^{-6}$ cts/keV/kg_{iso}/yr

B. Mong, talk at Heavy Quarks and Leptons, Blacksburg, VA, 2016

A. Pocar, talk at NeuTel 2015, Venice, 2015.

nEXO Collaboration, arXiv:1710.05075

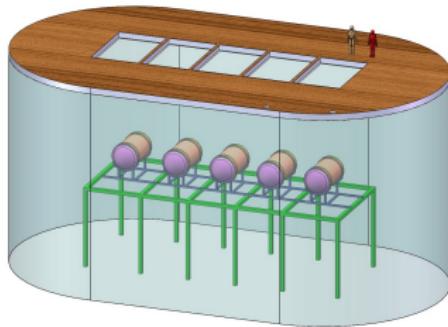
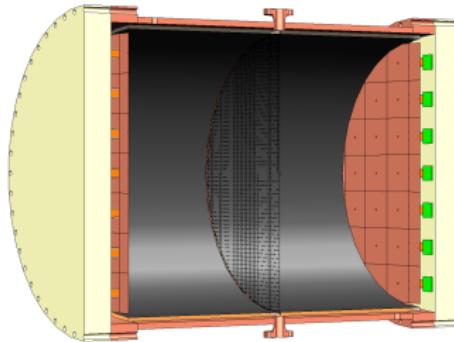


- High pressure xenon gas TPC \Rightarrow Single element + tracking + high resolution
- 0.75% FWHM proven in prototypes!
- Currently running with 5 kg, 100 kg phase expected in 2018,
 $BI = 10^{-4} \text{ cts}/(\text{keV}\cdot\text{kg}\cdot\text{yr})$
- Ton scale under design: 3 TPCs of 500 kg each, 0.5% FWHM,
 $BI = 10^{-5} \text{ cts}/(\text{keV}\cdot\text{kg}\cdot\text{yr})$
- Asymmetric ROI due to ^{214}Bi line close to $Q_{\beta\beta}$

NEXT Collaboration, JINST 7 (2012) T06001

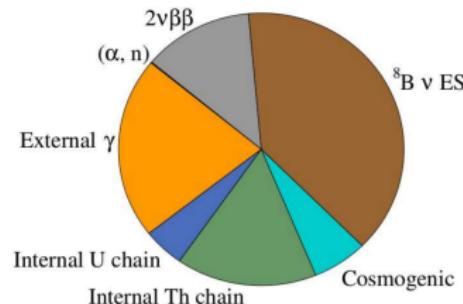
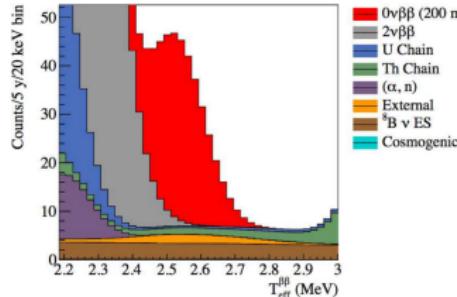
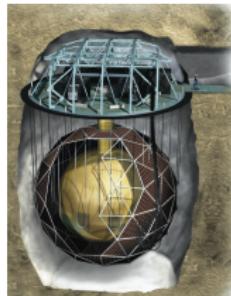
NEXT Collaboration, JHEP 1605 (2016) 159

J. J. Gomez-Cadenas, XLV International Meeting on Fundamental Physics, Granada, 2017



- High pressure xenon gas TPC
- Cathode in the middle, Micromegas readout at the anodes
- Two phases: 200 kg and 1 k (5×200 kg)
- Expected 3% FWHM for PandaX-II 200, and 1% for PandaX-III 1k
- 40 kg single-ended prototype currently functioning

X. Chen et al., Sci. China Phys. Mech. Astron. 60 (2017) 061011

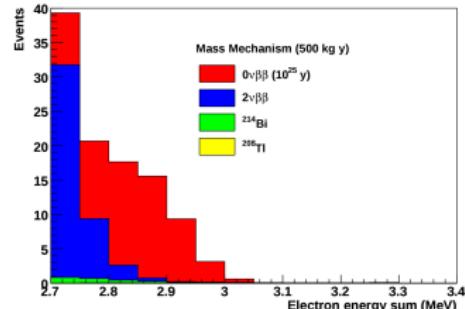
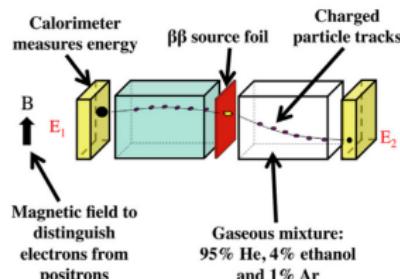
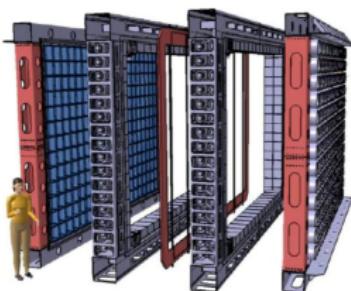


- Ongoing upgrade of SNO: acrylic sphere with 800 ton of ^{130}Te loaded LAB
- Existing infrastructure, easily scalable, self-shielding
- Phase I: 1.3 ton of ^{130}Te , 7.5% FWHM
- Phase II: \sim 8 ton of ^{130}Te , 5.3% FWHM (light detector upgrade)
- Limited resolution \Rightarrow asymmetric ROI
- Currently commissioning Phase I

SNO+ Collaboration, Proceeding for Magellan Workshop : Connecting Neutrino Physics and Astronomy, Hamburg, 2016

K. Singh, talk at Double Beta Decay 2016, Osaka, 2016

J. Klein, talk at NSAC NLDBD Review, Washington, DC, 2016.



- Successor of NEMO-3: 2 times lower resolution, 50 times lower background, 14 times more mass
- Source \neq detector
- 20 tracking chambers, each with 5 kg of ^{82}Se each in Mylar foils
⇒ Charge collection inefficiency, peak NOT at $Q_{\beta\beta}$
- Total efficiency hacked from plot: $\epsilon_{tot} = \epsilon_{\Delta E} \cdot \epsilon_{sig} = 16.5\%$
- First module almost completed, foils under installation

SuperNEMO, Nucl. Instrum. Meth. A 845 (2017) 398-403

SuperNEMO Collaboration, Eur. Phys. J. C 70 (2010) 927-943

SuperNEMO Collaboration, Nucl. Instrum. Meth. A 824 (2016) 507-509

Discovery sensitivity

- Value of $T_{1/2}^{0\nu}$ or $m_{\beta\beta}$ for which an experiment has a 50% chance to measure a signal above background with $\geq 3\sigma$ significance
- Computed as:

$$\hat{T}_{1/2}^{0\nu} = \ln 2 \frac{N_A \mathcal{E}}{m_a S_{3\sigma}(B)} \quad \text{with } B = \mathcal{B} \mathcal{E}$$

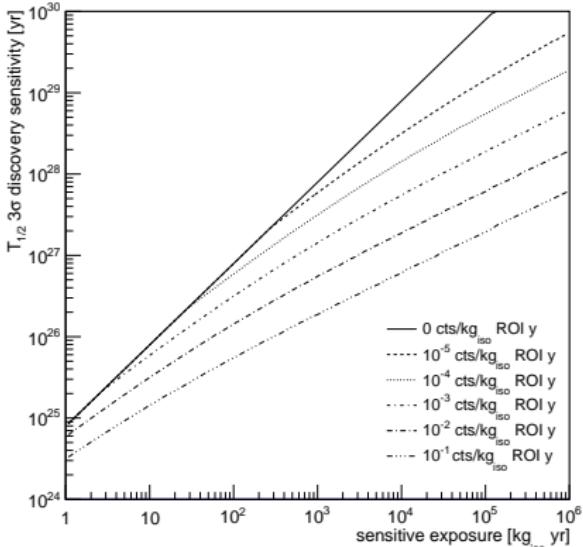
- $S_{3\sigma}(B)$ = Poisson signal expectation at which 50% of identical experiments report a 3σ upwards fluctuation above B
- If B large $\Rightarrow S_{3\sigma}(B) \propto \sqrt{B}$
- If $B \ll 1 \Rightarrow S_{3\sigma}(B) = \text{constant}$
- Find number of counts $C_{3\sigma}$ such that $CDF(C_{3\sigma}|B) = 3\sigma$, with CDF the cumulative of a Poisson distribution of mean B
 \Rightarrow Solve $1 - CDF(C_{3\sigma}|S_{3\sigma} + B) = 50\%$ to find $S_{3\sigma}$

Avoiding discrete jumps

- $C_{3\sigma}$ is integer
⇒ $S_{3\sigma}$ has discrete jumps
- Define $CDF_{Poisson}$ with normalized upper incomplete gamma function to make it continuous:

$$CDF_{Poisson}(C|\mu) = \frac{\Gamma(C+1|\mu)}{\Gamma(C+1)}$$

- Greatly improves computation speed (no toy-MC needed)
- Combination of data sets with different \mathcal{E} and \mathcal{B} results in smooth curve well represented by $S_{3\sigma}(B)$



- Example: ^{76}Ge
- For other isotopes, just rescale by molar mass

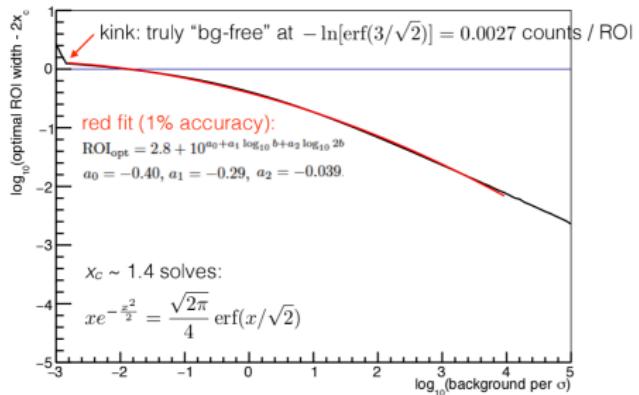
Heuristic counting analysis

ROI optimization

- For high resolution and flat background around $Q_{\beta\beta}$, maximize figure-of-merit:

$$F.O.M. = \frac{\text{erf}(n/2)}{S_{3\sigma}(bn)}$$

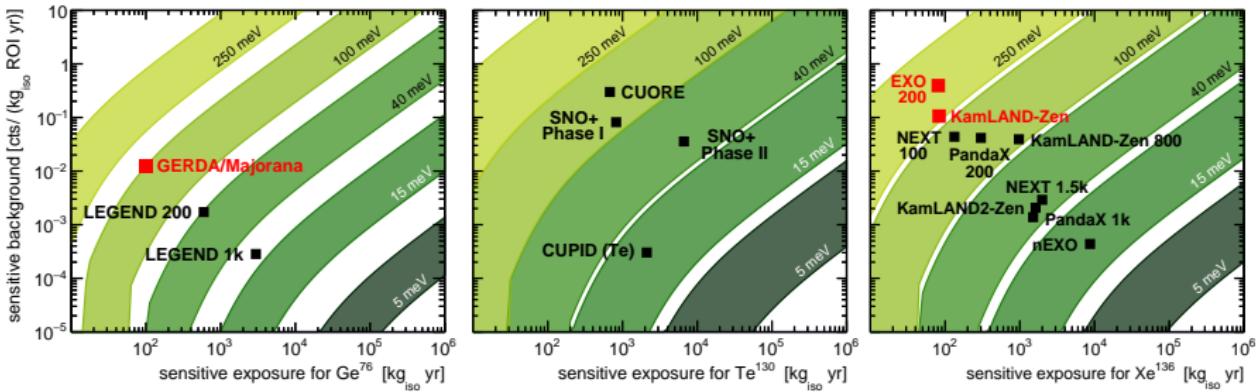
- n = ROI half-width in units of σ
- b = background counts per unit σ in 5 years of live time
- Large background: $S_{3\sigma}(bn) \propto \sqrt{bn}$
⇒ Optimal ROI: 2.8σ
- Background-free case: numerical solution ⇒ Optimal ROI: 4σ



Results: discovery sensitivity

Experiment	Iso.	Iso. Mass	σ	ROI	ϵ_{FV}	ϵ_{sig}	\mathcal{E}	\mathcal{B}	3 σ disc. sens.	Required Improvement			
	[kg _{iso}]	[keV]	[σ]	[%]	[%]	$\left[\frac{\text{kg}_{iso} \text{ yr}}{\text{yr}} \right]$	$\left[\frac{\text{cts}}{\text{kg}_{iso} \text{ ROI yr}} \right]$	$\hat{T}_{1/2}$ [yr]	$\hat{m}_{\beta\beta}$ [meV]	Bkg	σ	Iso. Mass	
LEGEND 200	⁷⁶ Ge	175	1.3	[-2, 2]	93	77	119	$1.7 \cdot 10^{-3}$	$8.4 \cdot 10^{26}$	40–73	3	1	5.7
LEGEND 1k	⁷⁶ Ge	873	1.3	[-2, 2]	93	77	593	$2.8 \cdot 10^{-4}$	$4.5 \cdot 10^{27}$	17–31	18	1	29
SuperNEMO	⁸² Se	100	51	[-4, 2]	100	16	16.5	$4.9 \cdot 10^{-2}$	$6.1 \cdot 10^{25}$	82–138	49	2	14
CUPID	⁸² Se	336	2.1	[-2, 2]	100	69	221	$5.2 \cdot 10^{-4}$	$1.8 \cdot 10^{27}$	15–25	n/a	6	n/a
CUORE	¹³⁰ Te	206	2.1	[-1.4, 1.4]	100	81	141	$3.1 \cdot 10^{-1}$	$5.4 \cdot 10^{25}$	66–164	6	1	19
CUPID	¹³⁰ Te	543	2.1	[-2, 2]	100	81	422	$3.0 \cdot 10^{-4}$	$2.1 \cdot 10^{27}$	11–26	3000	1	50
SNO+ Phase I	¹³⁰ Te	1357	82	[-0.5, 1.5]	20	97	164	$8.2 \cdot 10^{-2}$	$1.1 \cdot 10^{26}$	46–115	n/a	n/a	n/a
SNO+ Phase II	¹³⁰ Te	7960	57	[-0.5, 1.5]	28	97	1326	$3.6 \cdot 10^{-2}$	$4.8 \cdot 10^{26}$	22–54	n/a	n/a	n/a
KamLAND-Zen 800	¹³⁶ Xe	750	114	[0, 1.4]	64	97	194	$3.9 \cdot 10^{-2}$	$1.6 \cdot 10^{26}$	47–108	1.5	1	2.1
KamLAND2-Zen	¹³⁶ Xe	1000	60	[0, 1.4]	80	97	325	$2.1 \cdot 10^{-3}$	$8.0 \cdot 10^{26}$	21–49	15	2	2.9
nEXO	¹³⁶ Xe	4507	25	[-1.2, 1.2]	60	85	1741	$4.4 \cdot 10^{-4}$	$4.1 \cdot 10^{27}$	9–22	400	1.2	30
NEXT 100	¹³⁶ Xe	91	7.8	[-1.3, 2.4]	88	37	26.5	$4.4 \cdot 10^{-2}$	$5.3 \cdot 10^{25}$	82–189	n/a	1	20
NEXT 1.5k	¹³⁶ Xe	1367	5.2	[-1.3, 2.4]	88	37	398	$2.9 \cdot 10^{-3}$	$7.9 \cdot 10^{26}$	21–49	n/a	1	300
PandaX-III 200	¹³⁶ Xe	180	31	[-2, 2]	100	35	60.2	$4.2 \cdot 10^{-2}$	$8.3 \cdot 10^{25}$	65–150	n/a	n/a	n/a
PandaX-III 1k	¹³⁶ Xe	901	10	[-2, 2]	100	35	301	$1.4 \cdot 10^{-3}$	$9.0 \cdot 10^{26}$	20–46	n/a	n/a	n/a

Results: discovery sensitivity



- 15 meV band corresponds to the end of IO region
- Red dots: published limits
- Black dots: 3 σ discovery sensitivities with 5 yr live time
- Discovery sensitivity after 10 yr is $\sim \sqrt{2}$ higher for all experiments
- Bands represent NME spread

$0\nu\beta\beta$ decay with light neutrino exchange

Assumptions

- 0) Flavor and mass neutrino eigenstates: $\nu_l = \sum_i U_{li} \nu_i$.
- 1) Only 3 known neutrinos are involved
- 2) Neutrinos have a Majorana mass term in the SM Lagrangian. We don't consider an additional Dirac term or additional fields.

Lagrangian for Majorana mass

$$\mathcal{L}_M = \sum_{l,l'=e,\mu,\tau} \frac{m_{\nu_l, \nu_{l'}}}{2} \nu_l^t(x) C^{-1} \nu_{l'}(x) + h.c.$$

Effective Majorana mass

$$m_{\beta\beta} = |m_{\nu_e, \nu_e}| = \left| \sum_{i=1}^3 U_{ei}^2 m_i \right|$$

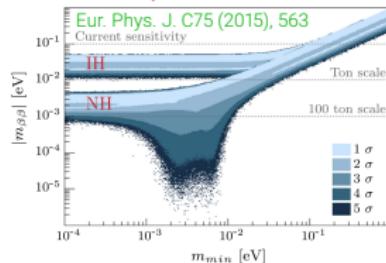
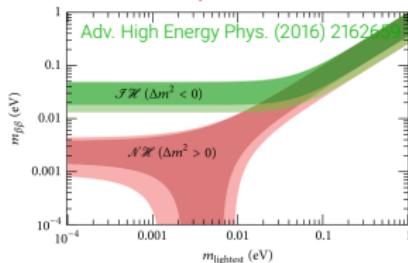
$$U = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\frac{\delta_{CP}}{2}} \\ \dots & \dots & \dots \\ \dots & \dots & \dots \end{pmatrix} \cdot \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\frac{\alpha_{21}}{2}} & 0 \\ 0 & 0 & e^{i\frac{\alpha_{31}}{2}} \end{pmatrix} = \begin{array}{l} \text{PMNS mixing matrix} \\ \text{with Majorana phases} \end{array}$$

Discovery probability with light neutrino exchange

Bayesian method offers natural way to approach the problem:

$$\text{DP} = \frac{\text{Region of parameter space for which } a \geq 3\sigma \text{ discovery is possible}}{\text{Total parameter space volume}}$$
$$= \int_0^\infty \frac{dP(m_{\beta\beta})}{dm_{\beta\beta}} \cdot \overline{\text{CDF}}_{\text{Poisson}}(C_{3\sigma}|S(m_{\beta\beta}) + B) dm_{\beta\beta},$$

How to compute the total parameter space volume?



- we cannot even invoke 'naturalness' to argue that $m_{\beta\beta}$ should not be much smaller than its individual m_i -contributions. [...] some flavour symmetry could easily force a small $m_{\beta\beta}$, giving rise to apparently unnatural cancellations [...]*
- On the other hand, several mass models do NOT predict specific values of $m_{\beta\beta}$

* F. Feruglio, A. Strumia and F. Vissani, Nucl. Phys. B637 (2002) 345-377

Characteristics and limitations of our approach

- Use all information available to date to extract PDF of $m_{\beta\beta}$
 - ⇒ Need to interpret plot of $m_{\beta\beta}$ vs m_l as a 2-dim PDF
- Assumptions on neutrino masses folded in parameter basis and priors
- Need well-behaved (=normalizable) variables

Priors

- Masses: neutrino mass scale unknown
 - ⇒ log-flat priors
 - ⇒ Non-normalizable: need upper and lower cut-off. OK if data provide them.
- Angles: flat in $[0, 2\pi[$
- Phases: flat in $[0, 2\pi[$
 - ⇒ Not non-informative
 - ⇒ Profession of ignorance: invoke naturalness

Possible choices

- 1) Basic parameters of the theory: $\{m_1, m_2, m_3, \theta_{12}, \theta_{13}, \alpha_{21}, (\alpha_{31} - \delta_{CP})\}$
- 2) Observables: $\{\Sigma/m_\beta/m_{\beta\beta}, \Delta m_{21}^2, |\Delta m_{3l}^2|, \theta_{12}, \theta_{13}, \alpha_{21}, (\alpha_{31} - \delta_{CP})\}$
- 3) A mix of basic parameters and observables

Our choice

- We are 3 experimentalist \Rightarrow Option (2)
- "Official" results obtained with $\{\Sigma, \Delta m_{21}^2, |\Delta m_{3l}^2|, \theta_{12}, \theta_{13}, \alpha_{21}, (\alpha_{31} - \delta_{CP})\}$
- Cross-check using m_β and $m_{\beta\beta}$ instead of Σ
- $m_{lightest}$ considered separately because it would involve the use of an arbitrary cut-off to make its prior normalizable
- Choosing a base with $m_{lightest}$ instead of Σ corresponds to the assumption of hierarchical vs non-hierarchical neutrino masses

Global fit: likelihood

$$\begin{aligned}\mathcal{L} = & \mathcal{L}(\mathcal{D}_{osc} | \Delta m_{21}^2) \cdot \mathcal{L}(\mathcal{D}_{osc} | \Delta m_{31}^2 / \Delta m_{23}) \\ & \cdot \mathcal{L}(\mathcal{D}_{osc} | s_{12}^2) \cdot \mathcal{L}(\mathcal{D}_{osc} | s_{13}^2) \\ & \cdot \mathcal{L}(\mathcal{D}_{Troitsk} | m_\beta) \cdot \mathcal{L}(\mathcal{D}_{0\nu\beta\beta} | m_{\beta\beta})\end{aligned}$$

- \mathcal{D}_{osc} = posteriors from nu-fit
- $\mathcal{D}_{Troitsk}$ = Bayesian limit from Troitsk experiment
- $\mathcal{D}_{0\nu\beta\beta}$ = Power-constrained combination* of GERDA and KZ sensitivities due to presence of background under-fluctuations

Exponential limit

$$f(x) = -\frac{\ln(1 - C.I.)}{t} \cdot \exp\left(\frac{\ln(1 - C.I.)}{t} \cdot x\right) \quad \text{with } t \text{ limit at given } C.I.$$

Power-constrained combination

$$f(x) = -\frac{\ln(1 - C.I._1)}{t_1} \cdot \frac{\ln(1 - C.I._2)}{t_2} \cdot \exp\left[\left(\frac{\ln(1 - C.I._1)}{t_1} + \frac{\ln(1 - C.I._2)}{t_2}\right) \cdot x\right]$$

* G. Cowan et al., arXiv:1105.2166

Current knowledge: oscillation experiments

- Measured well: Δm_{21}^2 and $|\Delta m_{3l}^2|$ ($l = \text{lightest}$) and angles $\theta_{12}, \theta_{13}, \theta_{23}$.
⇒ All uncorrelated except θ_{23} , which does not enter $m_{\beta\beta}$
- Sign of Δm_{31}^2 not known
⇒ NO for $\Delta m_{31}^2 > 0$, IO for $\Delta m_{31}^2 < 0$
- Weak information on δ_{CP}
⇒ For flat assumption on α_{31} , it does not enter $m_{\beta\beta}$
- Distributions from nu-fit

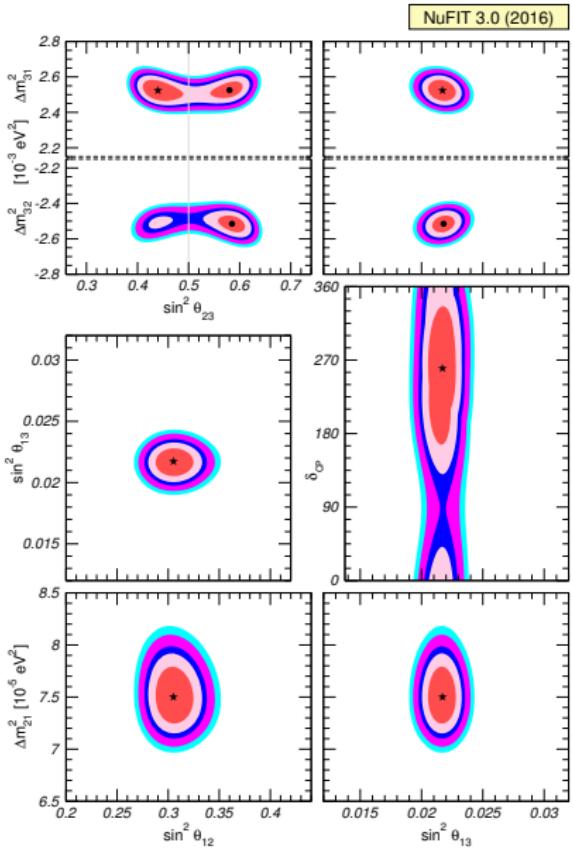
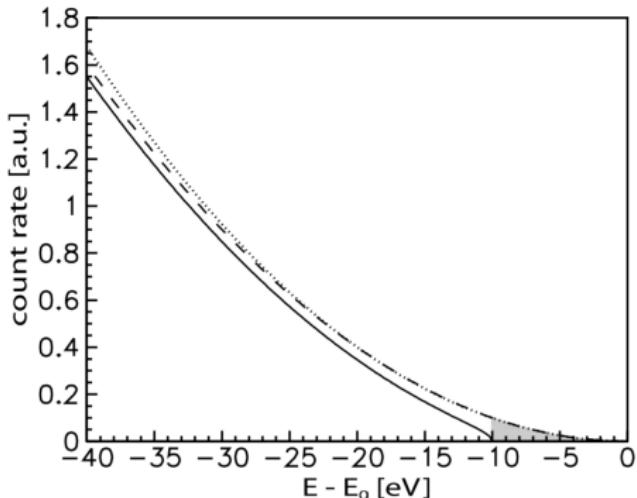


Figure from: I. Esteban et al., JHEP 01 (2017) 087

Current knowledge: end-point of β decay spectrum



- Physical Observable: effective ν_e mass:

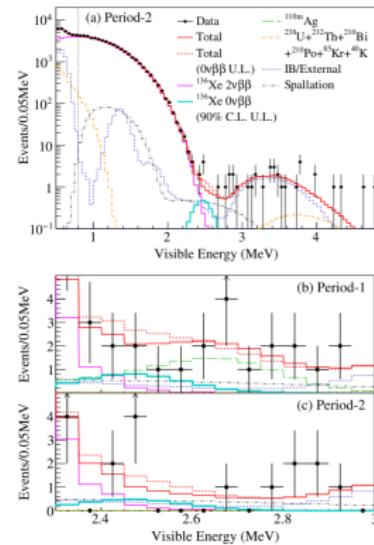
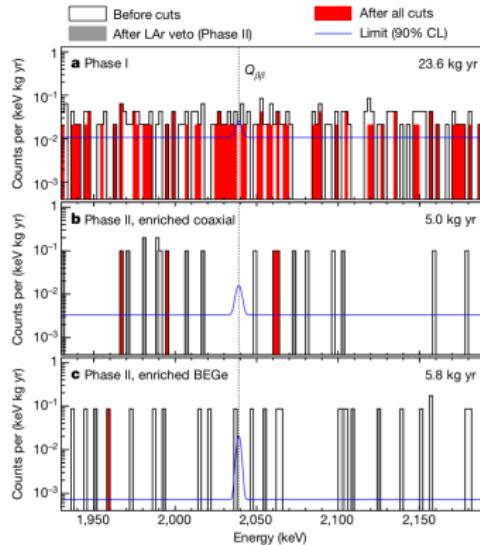
$$m_\beta = \sqrt{m_1^2 c_{12}^2 c_{13}^2 + m_2^2 s_{12}^2 c_{13}^2 + m_3^2 s_{13}^2}$$

- Assumptions **0** (flavor-mass eigenstates) and **1** (3 ν 's) are enough
- Troitsk Bayesian limit: $m_\beta < 2.12$ eV (95% C.I.)*
- Mainz frequentist limit: $m_\beta < 2.3$ eV (95% C.L.)†
- Overall, much weaker information than from other experimental observables

* V. N. Aseev et al., Phys. Rev. D 84 (2011) 112003

† Ch. Kraus et al., Eur. Phys. J. C 40 (2005) 447-468

Current knowledge: $0\nu\beta\beta$ decay experiments



- Experiments sensitive to $T_{1/2}^{0\nu}$. Translation to $m_{\beta\beta}$ involves assumption (2)
- GERDA: $T_{1/2}^{0\nu}(^{76}\text{Ge}) > 5.3 \cdot 10^{25} \text{ yr}$ (90% C.L.) $\Rightarrow m_{\beta\beta} < 150 - 330 \text{ meV}^*$
Exclusion sensitivity: $\hat{T}_{1/2}^{0\nu}(^{76}\text{Ge}) = 4.0 \cdot 10^{25} \text{ yr}$ $\Rightarrow \hat{m}_{\beta\beta} = 200 - 430 \text{ meV}$
- KamLAND-Zen: $T_{1/2}^{0\nu}(^{136}\text{Xe}) > 1.07 \cdot 10^{26} \text{ yr}$ (90% C.L.) $\Rightarrow m_{\beta\beta} < 61 - 165 \text{ meV}^\dagger$
Exclusion sensitivity: $\hat{T}_{1/2}^{0\nu}(^{136}\text{Xe}) = 5.6 \cdot 10^{25} \text{ yr}$ $\Rightarrow \hat{m}_{\beta\beta} = 84 - 230 \text{ meV}$

* GERDA Collaboration, Nature 544 (2017) 47-52

† A. Gando et al., Phys. Rev. Lett. 117 (2016) 082503

Systematics: NME and quenching of g_A

Nuclear matrix elements

- Consider different nuclear models (QRPA, ISM, IBM-2, EDF)*
- Use average among independent results obtained with the same method
- Run fit for each set of NME separately, then quote max and min

Quenching of g_A

- Axial-vector coupling enters NME as g_A^2
- For some nuclear models, g_A seems to be quenched by up to 30% as a function of $Z \Rightarrow$ Effect on $m_{\beta\beta}$ potentially large!
- Repeat fit with 30% quenching and quote difference

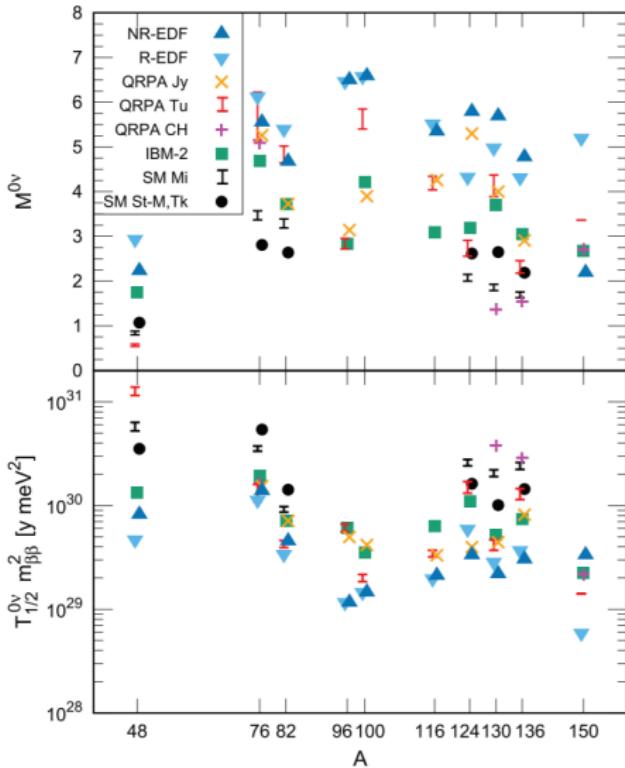
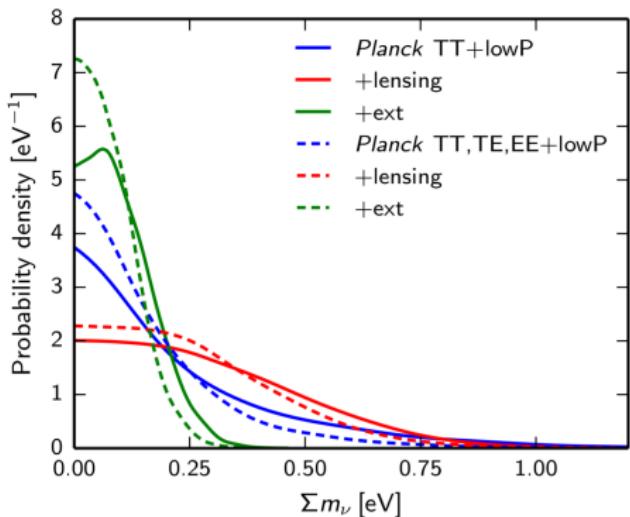


Image from J. Engel and J. Menendéz, Rept. Prog. Phys. 80 (2017) 046301

Systematics: cosmology and $m_{lightest} \rightarrow 0$

Cosmological constraint

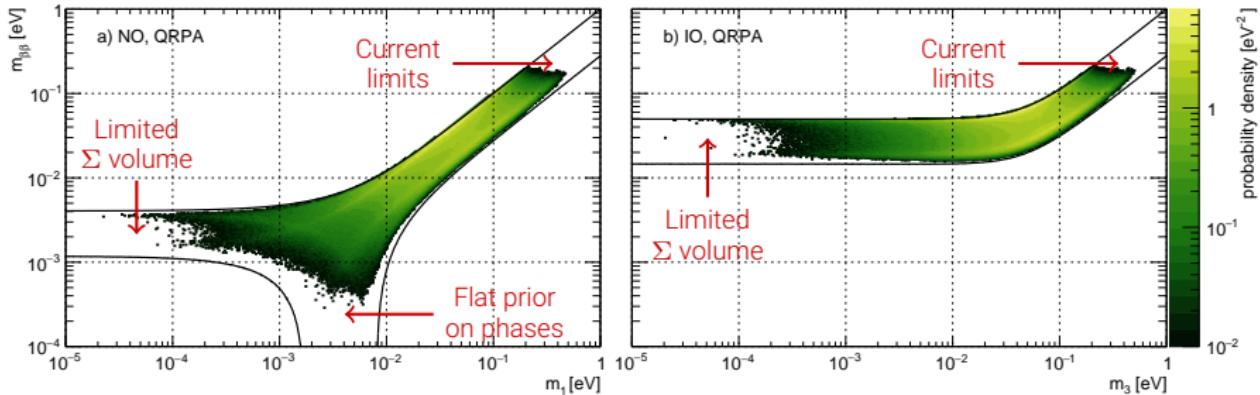
- Sensitive to the sum of neutrino masses: $\Sigma = m_1 + m_2 + m_3$
- Results depend on considered model and data set
⇒ More assumptions involved
- Repeat fit with additional term $L(D_{cosm}|\Sigma)$ and quote difference
- Use Planck "TT+lowP+lensing+ext" data set
- Repeat fit with Planck limit AND quenching of g_A



Case with $m_{lightest} \rightarrow 0$

- Represents the extreme case for hierarchical neutrinos

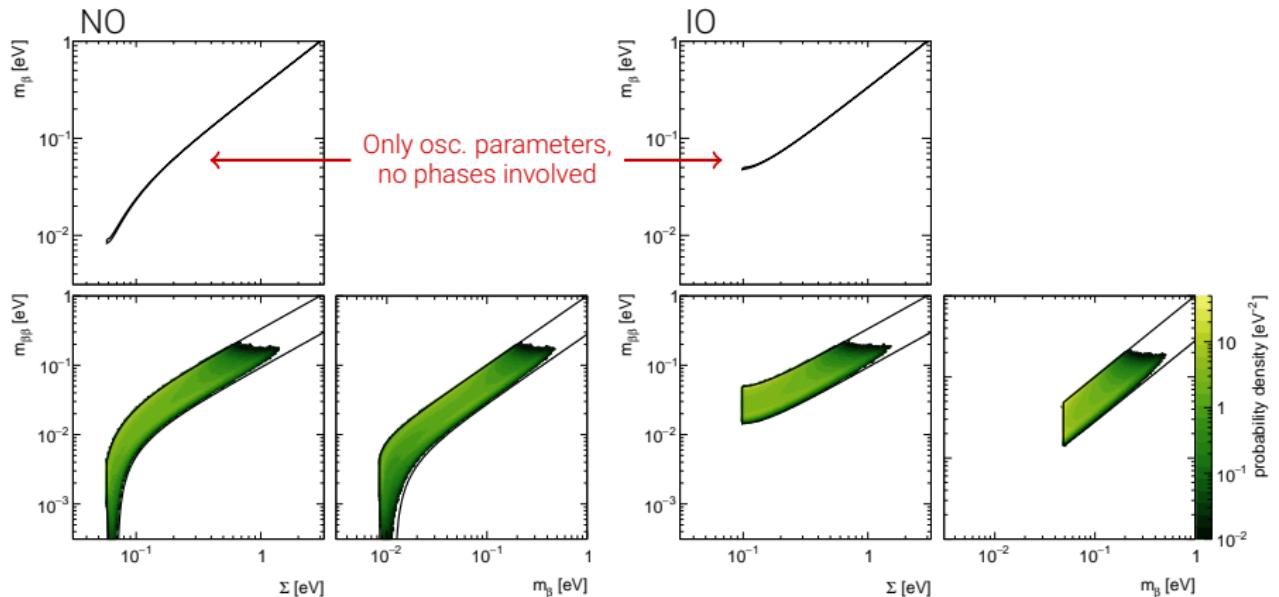
Results: $m_{\beta\beta}$ VS $m_{lightest}$



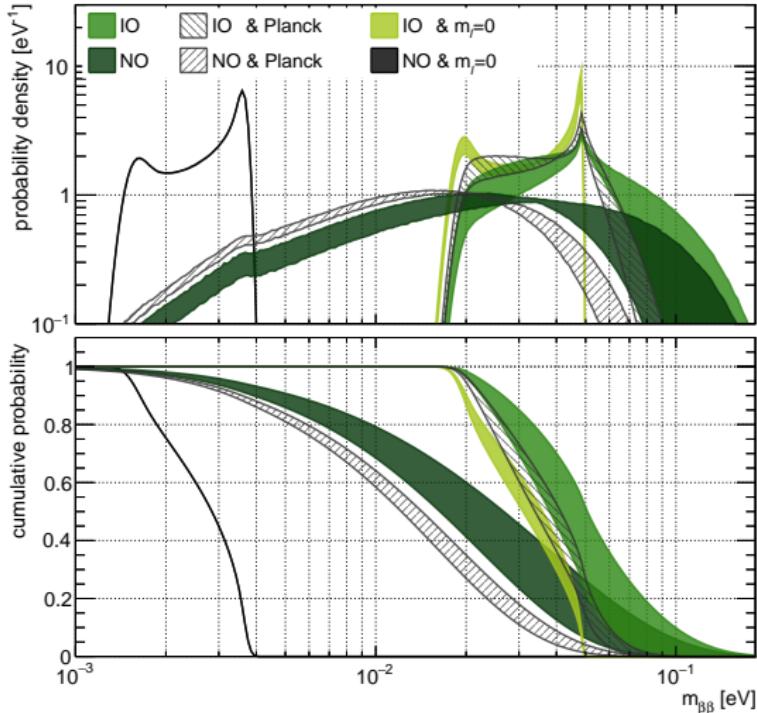
Caveats

- In NO, a flavor symmetry could induce an apparent fine tuning of the Majorana phases and a vanishing $m_{\beta\beta}$
- Mass mechanisms that drive m_l to zero are not considered
⇒ Just extrapolate down the horizontal bands

Results: $m_{\beta\beta}$ vs Σ and m_β

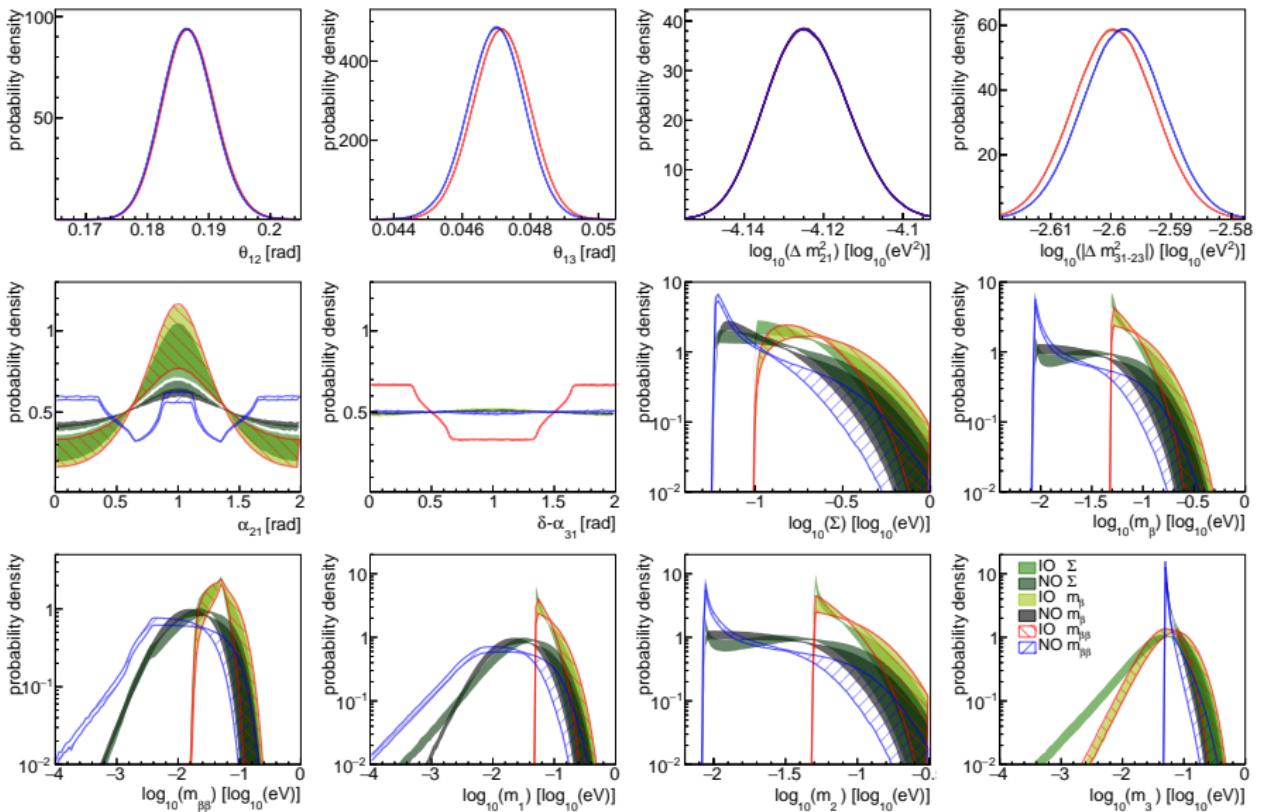


Results: $PDF(m_{\beta\beta})$ and $CDF(m_{\beta\beta})$

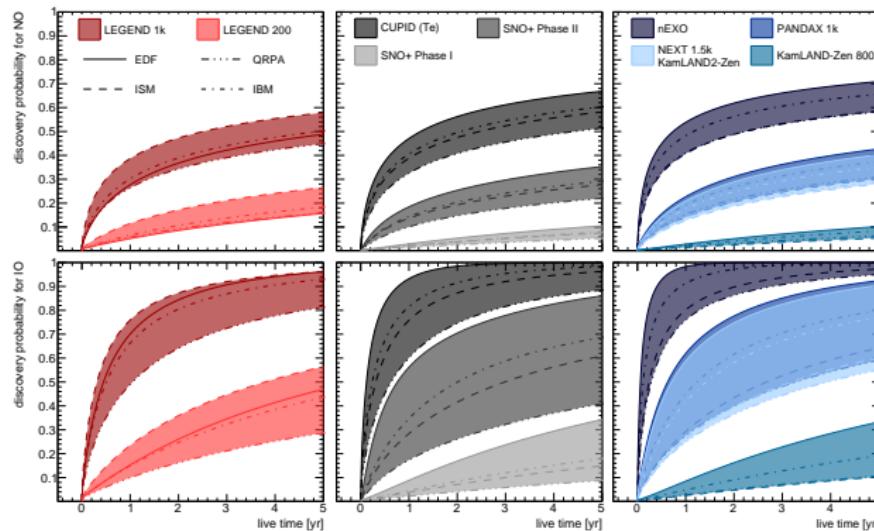


- Bands show NME variation
- Top: $P(m_{\beta\beta}|\mathcal{D})$
- Bottom:
$$\int_{m_{\beta\beta}}^{+\infty} P(m_{\beta\beta}|\mathcal{D}) dm_{\beta\beta}$$
- Planck limit reduces cumulative probability by $\sim 20\%$ for NO and $\sim 10\%$ for IO
- With $m_l = 0$, $m_{\beta\beta}$ pushed to horizontal bands
→ Small impact on DP for IO, huge for NO

Results: all posteriors



Results: discovery probability



- Fold $m_{\beta\beta}$ PDF with discovery sensitivity
- Bands represent NME maximal deviations
- Multi-isotope approach suggested!

DP for most promising experiments

- Reference analysis (quasi-degenerate neutrinos): $\sim 100\%$ for IO, $> 50\%$ for NO
- Hierarchical neutrinos ($m_l = 0$): $> 90\%$ for IO, $< 2\%$ for NO

Join the game: quantify your prejudice and extract your own DP!

- Example: 50:50 for IO:NO, 50:50 for H:QD \Rightarrow DP=60%

Alternative analyses

Cosmological limit

- For NO, discovery probability degrades by $\sim 30\%$
- For IO, difference at percent level

Quenching of g_A

- Quenching degrades discovery sensitivity as well as current limits
 \Rightarrow Effect on discovery potential smaller than on sensitivity
- 30% quenching reduces discovery potential by 15% for IO
- 30% quenching reduces discovery potential by 25% for NO

Cosmological limit AND quenching of g_A

- Region at high $m_{\beta\beta}$ stays disfavored \Rightarrow Reduced experimental reach
- Discovery power $\geq 50\%$ for IO
- Discovery power $O(10\%)$ for NO

What if KATRIN sees a signal?

- DP = 100% regardless of ordering, mass model, NME, quenching, cosmology

Summary and outlook

On which parameters should optimize and compare experimental designs?

- Sensitive background and exposure appear to be the appropriate parameters

What sensitivity is of interest?

- 3σ discovery \Rightarrow Computable without toy-MC

What is the DP of future experiments?

- DP for IO is as high as has been advertised by the experimental collaborations
- Surprisingly high DP for NO relative to the recent community perception, modulo the mass model bias \Rightarrow Highlights the importance of what we believe about how neutrinos get their mass
- Surprisingly robust against many of the “damning” impacts of IO/NO discrimination, g_A quenching, or cosmological limits
- We believe these arguments make a strong case for the value for investing in a global multi-isotope campaign to search for $0\nu\beta\beta$ decay at the IO scale

M. Agostini, G. Benato and J. A. Detwiler, Phys. Rev. D96 (2017) 053001